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Modelling surface runoff and soil erosion for Yen Bai Province, Vietnam, using the Soil and Water Assessment Tool (SWAT)

Mô Hình Hóa Nước Chảy Mặt và Xói Mòn Đất cho Tỉnh Yên Bái, Việt Nam Sử Dụng Mô Hình SWAT

Research article

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Applications of the Soil and Water Assessment Tool (SWAT) are common. However, few attempts have focused on the tropics like in the Yen Bai province, Vietnam. Annual water-induced soil erosion (WSE) rates and surface runoff (SR) were estimated. The Nam Kim and Ngoi Hut watersheds were calibrated with accepted agreement between simulated and observed discharge. Correlations between precipitation, land covers, surface runoff and WSE were indicated. Although the estimated average WSE 4.1 t ha^{-1} $year^{-1}$ (t ha^{-1} y^{-1}) was moderate, some steep-bare areas were suffering serious soil loss of 26 t ha^{-1} y^{-1} and 15% of the province was calculated at the rate of 8.5 t ha^{-1} y^{-1}. We found that the changes in WSE significantly correlated with land use changes. As calibrated SR matched closely with the measured data, we recommend SWAT applications for long-term soil erosion assessments in the tropics.

Những ứng dụng của mô hình công cụ đánh giá đất và nước (SWAT) đã được sử dụng phổ biến. Tuy nhiên có rất ít nghiên cứu tập trung vào khu vực nhiệt đới như tỉnh Yên Bái của Việt Nam. Trong nghiên cứu này, giá trị trung bình năm (2001-2012) nước chảy bề mặt (NCM) và xói mòn đất do nước (XM) đã được đánh giá trên cơ sở mô hình SWAT. Các thông số thủy văn của hai lưu vực sông là Nậm Kim và Ngòi Hút được tính toán và kiểm nghiệm với sự trùng hợp tương đối tốt giữa kết quả mô hình và số liệu thực đo. Mối liên hệ giữa lượng mưa, phủ bề mặt, NCM và XM cũng được phân tích và trình bầy chi tiết. Mặc dù giá trị XM năm được ước lượng ở mức trung bình cho toàn Tỉnh (4,1 tấn/ha/năm) nhưng ở một số khu vực nơi có độ dốc lớn và phủ mặt ít lại có lượng XM năm ở mức cao, 26 tấn/ha/năm và 15% tổng diện tích của Tỉnh có giá trị XM là 8,5 tấn/ha/năn. Kết quả nghiên cứu cho thấy sự liên hệ mật thiết giữa sự thay đổi phủ mặt tới giá trị XM. Trên cơ sở kết quả kiểm nghiệm mô hình khả quan, chúng tôi đề xuất sử dụng mô hình SWAT để đánh giá XM trong thời gian dài cho vùng nhiệt đới.

Keywords: GIS and remote sensing, hydrological modelling, surface runoff, SWAT, Yen Bai, water-induced erosion

1. Introduction

Soil denudation intensity is one of the most favoured topics (Ananda and Herath, 2003) in whole soil erosion and water-induced soil erosion (WSE) (Lopez-Vicente et al., 2013), in particular. The consequences of surface runoff (SR) and soil erosion increase the risk of declining land availability (Dercon et al., 2012) and downstream water quality (Arnhold et al., 2014). Therefore, food security and sustainable development are the main problems in the reduced availability of land per capita countries (Dercon et al., 2012) such as in Vietnam with 2542 m^2 per capita in 1930 and 437 m^2 per capita in 2011 (VEM, 2012). However, land cover change and unsustainable agricultural practices in recent decades appear to be the main impact on land degradation (Baja et al., 2009; Bakimchandra, 2011). This has been estimated increasingly in recent decades and

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is due to inappropriate agri-cultural practices and social development. Since the 1960s WSE has been studied by various approaches (Evans, 2005). However, only a few studies have focused on the tropics. Reversely, WSE presents the main threat to agriculture in the Yen Bai province of Vietnam, where most people's livelihoods are based on cultivation.

The linkage between SR, WSE amplification, intensive land uses and deforestation has been analysed by various scientists, for example David et al. (2014), and Lopez-Vicente et al. (2013). Since the vegetative cover has been reduced, the soil protection index (SPI-which is a function of land use and land cover (LULC) and Normalized Difference Vegetation Index) has been decreased (Bakimchandra, 2011) or the soil has become less resistant to the erosive force of rain drops and runoff. These result in increasing run off, lower infiltration and eventually soil erosion exaggeration (Andrade et al., 2010). Other studies have focused on impacts of climate change on WSE intensity by increases of annual rainfall, temperature and extreme events (De Munck et al., 2008). However, Mukundan et al. (2013) found that soil erosion and sediment yield (SY) appeared to decrease due to the increase in soil moisture deficit and evapotranspiration. We hypothesized that the rates of soil erosion and sediment transport in Yen Bai would rise mainly due to the decline in vegetative cover.

Water-induced soil erosion assessments by modelling at hill-slope or larger scales have been conducted by many scientists e.g. Gumiere et al. (2011), and Routschek et al. (2014). The SWAT model is known worldwide and there are also many works using the SWAT model to investigate soil erosion by water, or to examine the precision of the model such as the studies of Zhang et al. (2008). Conversely, there have been only a few attempts which have tested the abilities of the SWAT model to the tropical regions. Although the SWAT was developed for dry areas, the algorithms inside the SWAT are able to be implemented in tropical regions and this was proven by the studies of Tibebe (2011) and Fukunaga et al. (2015). After considering the model's requirements, accuracy and outputs, the SWAT was considered suitable and selected for the long-term soil erosion assessment of this study. We took advantages of GIS and remote sensing techniques for the aim of WSE assessment.

The SWAT model showed its ability to generate river discharge matching closely with observed data. Unfortunately, daily measured SY was not available for model validation but the simulated WSE was compared with data from an existing map. The results also revealed the capacity of the model's application for the tropics with reliable outputs.

2. Study site

The study site is located within the Yen Bai province of Vietnam (Fig. 1), which is located in north-western Vietnam. The central coordinates that indicate the locality of the watershed are 104°30'9.0" E and 21°35'26.7" N. The area is 6883.5 km^2, with the mean elevation of 902 meters above the Bien Dong Sea level. Although the soil erosion rate of Yen Bai is not seen as the highest within the north of Vietnam, the region was chosen as a study area for this research project because of several dominant aspects that were taken into account, such as the typical climatic conditions, representative morphological characteristics, availability of data and the projected upward trend of WSE. Hydrologically, the province is in the three river basins of Da, Hong and Chay.

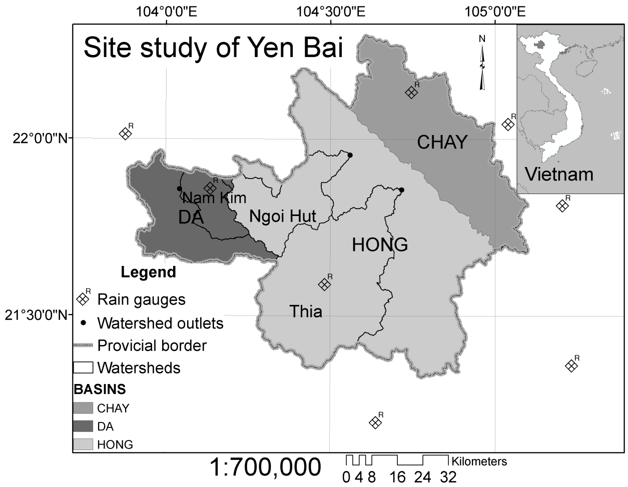

Figure 1. Yen Bai province and 3 watersheds chosen for model calibration and validation

The site has an annual average precipitation (no snow) of 1,638 mm and the rainfall covers mostly 85 percentage of the total value just in the rainy season from May to September (based on our acquired rainfall data from the 9 rain gauges). Additionally, the terrain of the study area is partitioned by dense stream networks and the average slope gradient was estimated to be 24.4 degrees. Morphologically, the site is considered as an erosive area.

3. Materials and methods

3.1 Modified soil loss equation

Soil erosion and SY are calculated for each hydrologic response unit (HRU) with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). Whilst within the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) precipitation is used as an indicatory force of erosive energy, MUSLE however employs the amount of runoff to estimate erosion and SY (Neitsch et al., 2009). Soil loss is estimated by means of the following equation (Williams, 1995):

$$sed = 11.8 \cdot \left(Q_{\mathrm{surf}} \cdot q_{\mathrm{peak}} \cdot area_{\mathrm{hru}}\right)^{0.56} \cdot K_{\mathrm{USLE}} \cdot C_{\mathrm{USLE}} \cdot P_{\mathrm{USLE}} \cdot LS_{\mathrm{USLE}} \cdot CFRG \quad (1)$$

Where, sed refers to the SY on any given day (t), Q_{surf} is the volume of surface runoff (mm ha^{-1}), q_{peak} is the peak runoff rate (m^3 s^{-1}), $area_{\mathrm{hru}}$ is the area of the HRU (ha). K_{USLE}, C_{USLE}, P_{USLE} and LS_{USLE} are the USLE soil erodibility factor, cover and management factor, support practice factor and topographic factor, respectively. The $CFRG$ indicates the coarse fragment factor of the soil. The details of the above components of the equation 1 are presented in the literature of Wischmeier and Smith (1978), Arnold and Williams (1995).

3.2 SCS-Curve Number method

The surface runoff can be estimated by one of the following two provided methods. These include the SCS-CN (Soil Conservation Service-Curve Number) method (USDA-SCS, 1972) and the Green–Ampt infiltration method (Green and Ampt, 1911). The CN is broadly employed and estimated based on the area's hydrologic soil group, land use, treatment and hydrologic condition. The CN range is from 30 to 100; lower values indicate low runoff potential while larger numbers show higher runoff potential. The higher CN values indicate the greater ability of infiltration (USDA-SCS, 1986). The direct runoff from a rainfall event in a particular area is determined efficiently using CN.

In this study, the former approach (USDA-SCS, 1972) has been used. The run-off value can be calculated as:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - I_{\text{a}})^2}{(R_{\text{day}} - I_{\text{a}} - S)} \qquad (2)$$

Where, Q_{surf} refers to the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the specific day (mm), I_{a} is the initial abstractions, which includes surface-water storage, interception and infiltration prior to runoff (mm) and S indicates the retention parameter (mm). Equation (2) indicates that the runoff will only occur when the $R_{\text{day}} > I_{\text{a}}$. The changing soils, land use practices, management regimes and slope, will temporally result in the varying of the S -value, because of changes in soil-water content.

The retention parameter can be calculated as follows:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (3)$$

Where, CN refers to the curve number for the day. The initial abstractions, I_{a} is frequently estimated as 0.2 S and the equation (2) is rewritten as:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - 0.2S)^2}{(R_{\text{day}} + 0.8S)}$$

3.3 Model inputs

3.3.1 Topography and river network

The morphological dataset used for watershed delineations, discretization, delineated drainage network. The DEM was produced by Vietnam Resources and Environment Corporation in 2009 employing Aerial Photogrammetry technology from the Intergraph Corporation, USA.

3.3.2 Land use and land cover (LULC)

Different LULC maps of the study site were prepared using Landsat TM imagery acquired on 28th January 2002 and 30th September 2009 for testing the impacts of land use changes on surface runoff and SY. The ground control points and ground-truth data were extracted from the Yen Bai geodatabase for geometric corrections and the supervised maximum likelihood classified method, respectively.

Table 1. LULC classification accuracy assessment

LULC (year)	P/U (%)	Forest	Lake	River	Urban	Agriculture	Shrubland	Grassland	Barren	O (%)	Kappa
2002	P	78.0	82.4	57.5	73.6	61.1	61.8	61.5	76.2	69.3	0.648
	U	72.1	73.9	61.1	73.3	65.6	65.0	63.7	77.2		
2009	P	86.2	88.8	76.3	72.3	73.4	73.8	64.0	74.7	76.8	0.734
	U	86.5	82.7	74.7	75.2	68.8	73.1	73.3	78.7		

P= Producer accuracy, U= User accuracy, O= Overall accuracy, and Kappa is the kappa statistic or kappa coefficient.

The LULC was classified into nine classes for each map as shown on the Figure 2. The Kappa statistics (Berry, 1992) producer accuracy and user accuracy were assessed for each class of the maps and written in Table 1. The average Kappa statistic of 0.7 was calculated and asserted a substantial agreement based on Viera & Garrett (2005).

3.3.3 Soils

The Yen Bai custom soil (YBS) map below generated in the MapInfo software in 1996 and set by the FAO/UNESCO norms for quality. Fifteen soil types were classified with their characteristics such as gradient (4 level of 0−8°, 8°−15°, 15°−25° and above 25°), soil thicknesses, soil texture, profiles etc. and divided into 6 major soil groupings including fluvisols, calcisols, ferralsols, alisols, acrisols and gleysols. The two dominant soils are Plinthic Ferralsols and Gleyic Alisols with distribution of 3855.8 and 998.6 km^2, respectively.

Secondly, the FAO Digitized Soil (FAO soils) Map of the World, version 3.6, was completed January 2003. Based on the FAO soils, only the two soil types are identified in the study region namely Ferric Acrisols and Orthic Acrisols.

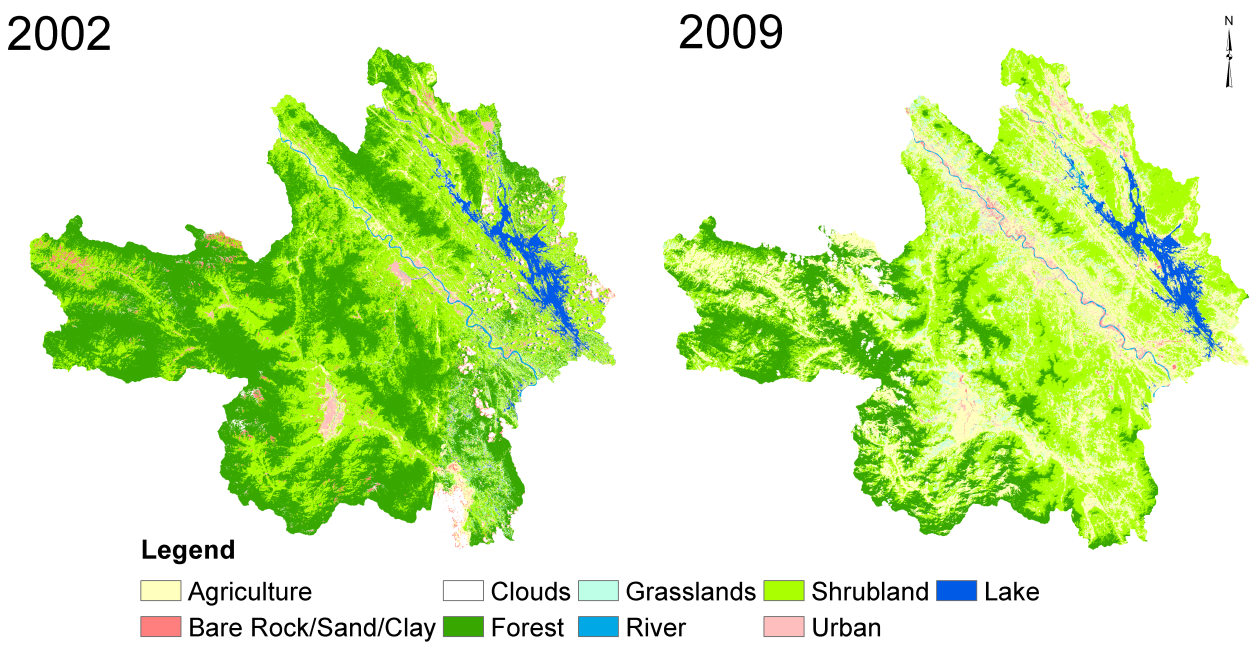

Figure 2. Maps of LULC mapped from Lansat TM scenes for Yen Bai province

3.3.4 Precipitation and temperature

Point measurements of daily rainfall and temperature were recorded by nine gauges (see Fig. 1) conducted inside the province and surroundings. The twelve-year daily data (from 01.01.2001 to 31.12.2012) was acquired and processed in Excel environment in order to generate the precipitation and temperature inputs for the SWAT model. Some short missing data was interpolated using the inverse-distance weighted equation (Shepard, 1986). Distributed data of precipitation and temperature were generated from gauged data using the Thiessen polygon method (Thiessen, 1911).

3.4 Model calibration, validation and simulation

Model calibration was done manually "by changing sensitive parameters" employing 5-year gauged data (daily and monthly) from 2001 to 2005. Some model sensitive parameters such as the CN, base flow recession and soil evaporation compensation were adjusted at this stage. Both the model calibration and validation (7-year periods of 2006-2012) were done for the Nam Kim and Ngoi Hut watersheds and the top-ten sensitive parameters are tabularised in the Table 2. The model performance was investigated by using the coefficient of determination (R^2), Nash–Sutcliffe coefficient of simulation efficiency (NSE) (Nash & Sutcliffe, 1970) values.

Table 2. SWAT initial and final calibrate parameters (NK = Nam Kim, NH =Ngoi Hut)

Parameter	Description	Unit	Range	Initial value	Final value (NK)	Final value (NH)
CN2	Curve number condition 2	–	35–98	35	54.1	48.7
Alpha_Bf	Baseflow recession constant	days	0–1	0.04	0.4	0.5
Ch_K2	Effective hydraulic conductivity in channel	mm hr^{-1}	−0.01–500	50	75	50
Sol_K	Saturated hydraulic conductivity	mm hr^{-1}	0–2000	2	4.30	16.03
Ch_N2	Manning n value for the main channel	–	−0.01–0.3	0.015	0.05	0.05
Surlag	Surface runoff lag coefficient	–	1–24	4	2.5	5.6
Sol_Awc	Available water capacity	mm mm^{-1}	0–1	0.22	0.31	0.35
Gw_Revap	Revap coefficient	–	0.02–0.2	0.02	0.2	0.2
Esco	Soil evaporation compensation factor	–	0–1	0	0.95	0.95
Gwqmin	Threshold water level in shallow aquifer for base flow	Mm	0–5000	0	1500	2000

4. Results and discussion

4.1 Monthly surface runoff

Figure 3 presents the 5-year results of the model calibration of monthly outflow from 2001 to 2005. Before model calibration (Figs 3a and b), basically there were underestimates of base flows and the peaks for both the Nam Kim (NSE=0.3, R^2 = 0.81) and Ngoi Hut (NSE = 0.1, R^2 = 0.39).

On the other hand, the model performed excellently with the calibrated discharge matching closely with the measured data for both the watersheds, verified by evaluating NSE of 0.86, R^2 = 0.87 for the Nam Kim and NSE of 0.81, R^2 = 0.76 for the Ngoi Hut (Figs. 3c and d), respectively. It was a result of alternation of the base flow recession, inter flow and other parameters.

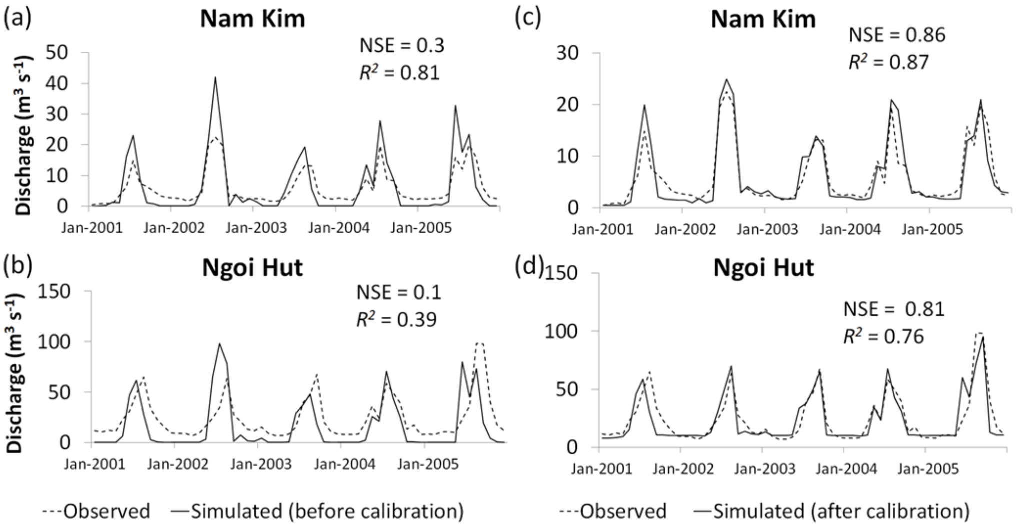

Figure 3. Observed and simulated monthly surface runoff before calibration (a and b) and after calibration (c and d)

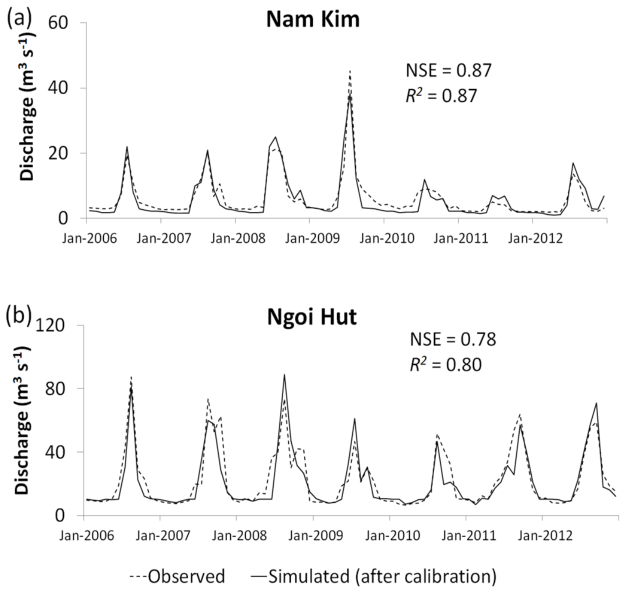

Figure 4. Observed and simulated monthly surface runoff for model validation (a) the Nam Kim (b) the Ngoi Hut

The good model results of monthly validation during the 7 years from 2006 to 2012 were illustrated on Figure 4 for the Nam Kim and Ngoi Hut. Based on the NSE and R^2 values, the model performed better with the smaller watershed (the Nam Kim-Fig. 4a with both the NSE and R^2 of 0.87) compared to the bigger one of the Ngoi Hut (Fig. 4b with NSE of 0.78, R^2 of 0.8). The figure also showed variations of runoff in rainy and dry seasons in quite big ranges of about 40 and 80 $m^3 s^{-1}$ for the Nam Kim and Ngoi Hut and the very consistent time of peaks in July (also in the calibration period). The two-year driest periods were from 2010 to 2011 in the Nam Kim and from 2009 to 2010 in the Ngoi Hut.

4.2 Relationships between annual precipitation, simulated surface runoff and sediment yield

In general, there were significant positive correlations between annual rainfall, surface runoff and SY in the three basins (Fig. 5) calculated for the 2001−2012 period indicated by coefficient of determinations. All of the R^2 values were larger than 0.65 (particularly 0.91 for the relationship between runoff and SY in the Hong basin). These results might reveal that the model estimates were possibly reasonable.

The figure also shows the simulated surface runoff and SY values for the three basins. Although the Chay had the highest annual mean precipitation (AMP) of 1800 mm, the average runoff (43 mm) and SY (1.7 t ha^{-1} y^{-1}) were not much higher than in the Hong basin (mean runoff of 36 (mm) and SY of 1.5 t ha^{-1} y^{-1}) with AMP of around 1400 (mm). The Da basin presented the most eroded area with an annual mean rate of over 4 (t ha^{-1} y^{-1}) and runoff of 60 (mm) but the AMP was 100 mm less than in the Chay. The high SR and SY rates of the Da could be explained by a positive proportional linkage between slopes and SR and SY values (Oliveira et al., 2013).

Figure 5 also indicates that in some wet years (AMP > 1800 mm) both the runoff and SY rates were higher than 60 (mm) and 5 (t ha^{-1} y^{-1}), respectively and particularly in the Da basin. On the other hand, in some dry years when the runoff rates were estimated less than 20 (mm), the SY values were nearly zero. That proved the changes in runoff and SY over the years were significant.

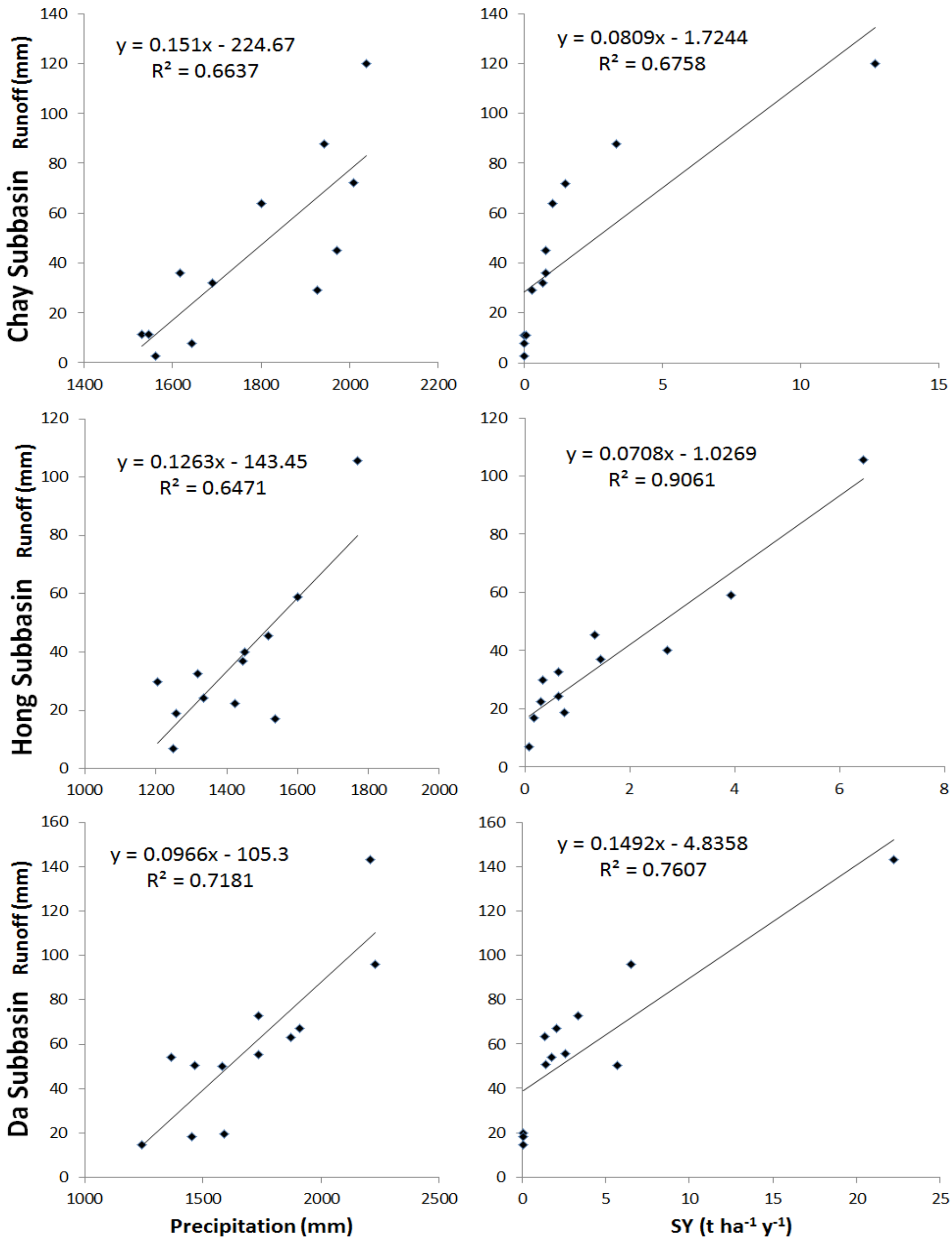

Figure 5. Correlations between annual rainfall, simulated surface runoff and sediment yield

4.3 Estimated soil loss for Yen Bai province comparing with data from the Atlas of Vietnam, 1997

Figure 6 shows estimated annual mean soil erosion rates (12-year) using different LULC and soil data compared with soil erosion map extracted from the VN-Atlas, 1997. The significant soil erosion areas were in Mu Cang Chai and Tram Tau districts and the moderate erosive areas were in the remaining districts in all cases. The maps also indicated the changes of land use (Figs 6a and b) effect on the soil erosion patterns. Some noted increases can be seen in the Mu Cang Chai, Van Yen and Van Chan districts with the dark-blue colours. The use of FAO soils (Fig. 6d) produced the coarse maps or some areas could be combined into one zone. On the other hand, the employment of the YBSs generated finer maps and is recommended to be used for provincial scale. Intuitively, the soil loss distributions shown on the map correlated well with the coarse map of the VN-Atlas, 1997 (Fig. 6c) even if they were in different scales.

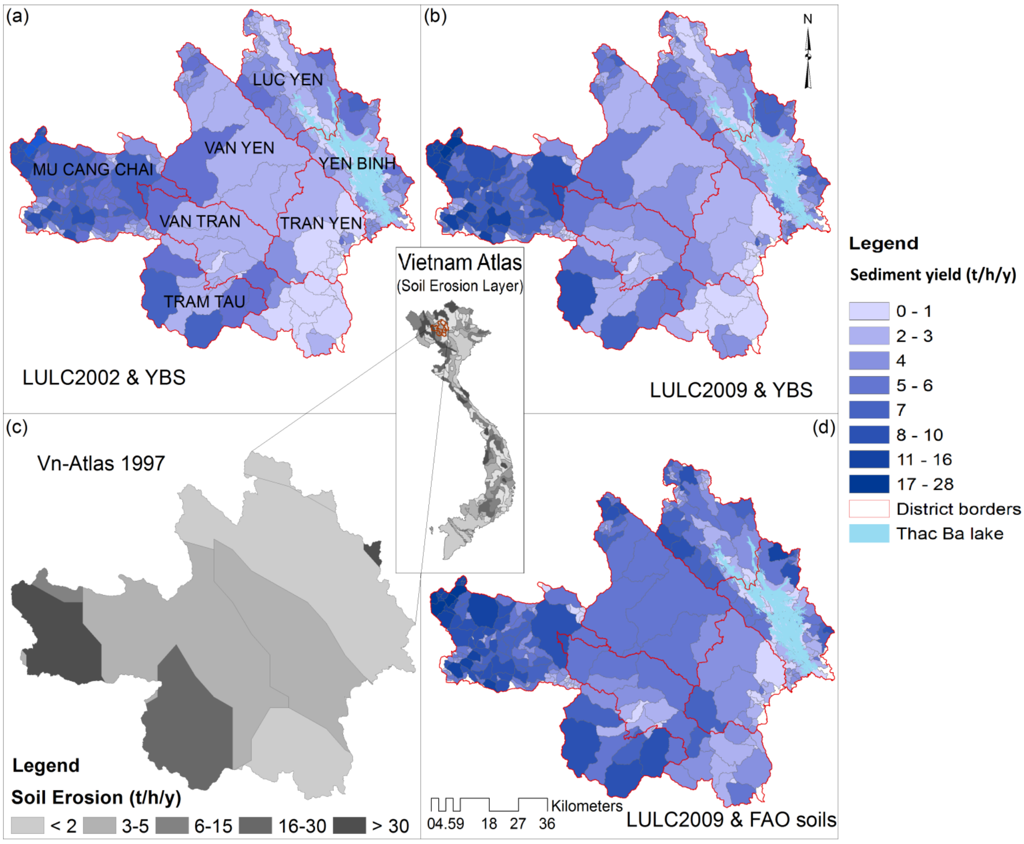

Figure 6. Observed and simulated monthly surface runoff for model validation (a) the Nam Kim (b) the Ngoi Hut

4.4 Land use changes effect on soil erosion distributions

One of the important assessments of this study is to evaluate to what extent the changes in LULC affect the annual mean soil erosion values. The results (Fig. 7) illustrated that reduction of the vegetative cover increased soil erosion rates and most of the red areas (increased from one to 3.3 t ha^{-1} y^{-1}) were the results of vegetation reductions and the increase in available agricultural land (compared with Fig. 2). Conversely, some areas were well protected by vegetative cover (in blue and light blue), possibly due to afforestation and decline in bare land.

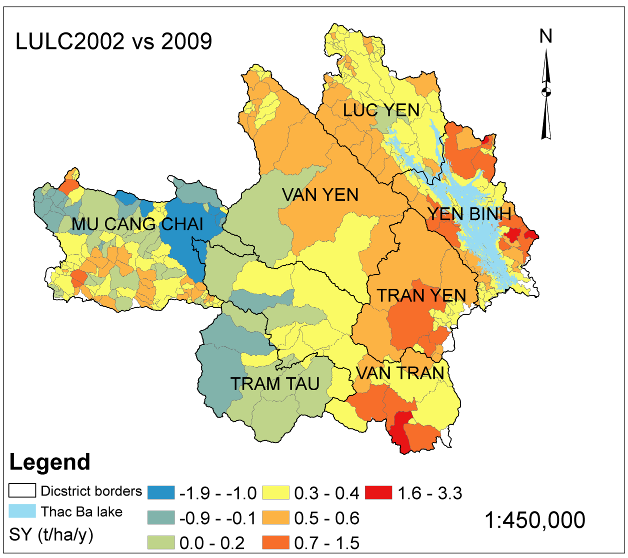

Figure 7. Map of soil erosion changes based on LULC2002 and 2009 conditions

5. Discussion and conclusion

At the model pre-calibration, the model underestimated the base flow and overestimated the peaks as well. A possible explanation for this might be that the model was originally developed for arid regions with low in flow and low soil moisture but computed for the tropics. However, the results of 5-year calibration and 7-year validation revealed that the monthly and daily simulated runoff matched closely with the measured discharge. This might indicate the flexibility of the model and that it could be adopted for the tropics in respect of surface runoff estimates. The study results could be archived better, if the input climate data were recorded for 20 years (Neitsch et al., 2009) or longer. For this remote-developing study site, the use of 12-year climatic data is acceptable but longer time-series climatic data is still needed for better accurate WSE estimation. In addition, the observed SY data is not available in the study site. Therefore, there is a need for in situ observations of model validation.

Beside the climatic and topographic aspects, the LULC plays an important role in shaping the soil erosion distributions. The reason for the increase of SY shown on the maps (Fig. 7) could be a reduction of vegetative cover during 2002 to 2009. This vegetative cover decrease led to higher estimated soil loss rates and this finding is in agreement with the findings of Baja et al. (2009) and Bakimchandra (2011). The increase in WSE rates might cause an increase in agricultural land and bare land, especially in the uplands (Abaci and Papanicolaou, 2009) of the region as well. As this role is significant, seasonal effects on LULC classification have to be taken in to account for classification accuracy and later on resulted in evaluating WSE (Karambiri et al., 2003 and Kefi et al., 2011). In the tropics, such as in the north of Vietnam, the agricultural land is cultivated very intensively, three or even more crops per year. This makes different reflectance on satellite scenes with different kinds of crops and, thus, sufficient ground-truth data (number of samples and being representative) has to be derived for the agricultural class. In addition, the annual soil erosion map derived from the Vn-Atlas, 1997 was assumingly not fine enough but it could somewhat verify the model's results. Remarkably, with the same inputs of the larger scale FAO soil map the model estimated a slightly higher SY rate. This was possibly due to a disappearance of water bodies in the map and in these areas the deposition processes are often more dominant rather than the erosive stages (Butt et al., 2010 and Schmengler, 2010).

An important finding is that the close linkages between annual rainfall, SR and SY were investigated for the 2001−2012 period and shown by the scattered graphs and equations. The equations and the R^2 values explained the logically good correlation between these factors. Surprisingly, the Da basin was found to be the most eroded area with precipitation lower than in the Chay. This rather contradictory result may be due to the strong linkage between slope, runoff and SY (the Da has the highest slope length and gradient). This relationship can also easily be seen in the equations 1 and 2 and explained more in Neitsch et al. (2009).

Generally, the positive proportional linkages between AMP, SR and SY were found from those simulated results for the three basins. Significantly, soil erosion rates were estimated by the model and summarized and mapped with a consideration of LULC changes. Although the on-site SY measurement was not available for model validation, equivalent rates and distribution between simulated and existing map data have been presented. From all these, the SWAT model provides an effective tool to estimate SR and WSE for tropical regions.

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